The Main Asteroid Belt
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The Dawn spacecraft is speeding through the inner solar system on its trajectory to the main asteroid belt to visit two of the largest protoplanets, Vesta and Ceres. Using sunlight, a mere 540 kilograms of xenon fuel, and a breathtakingly efficient ion engine, Dawn whizzes at speeds never accomplished by a spacecraft before. What compelled astronomers to send Dawn to the asteroid belt and what does the mission hope to learn when it gets there? To answer these questions we must first learn more about the main asteroid belt: Why it is where it is, the bodies that reside in it, and how we study them.

Where is the Main Asteroid Belt?

The main asteroid belt is the region in our solar system that lies between the orbits of Mars and Jupiter. Most of the asteroids in the main belt reside at a distance between 2.12 and 3.3 AU from the Sun. For reference, 1 AU is the average distance from the Sun to the Earth (http://astronomy.swin.edu.au/cms/astro/cosmos/A/Asteroid+Belt).

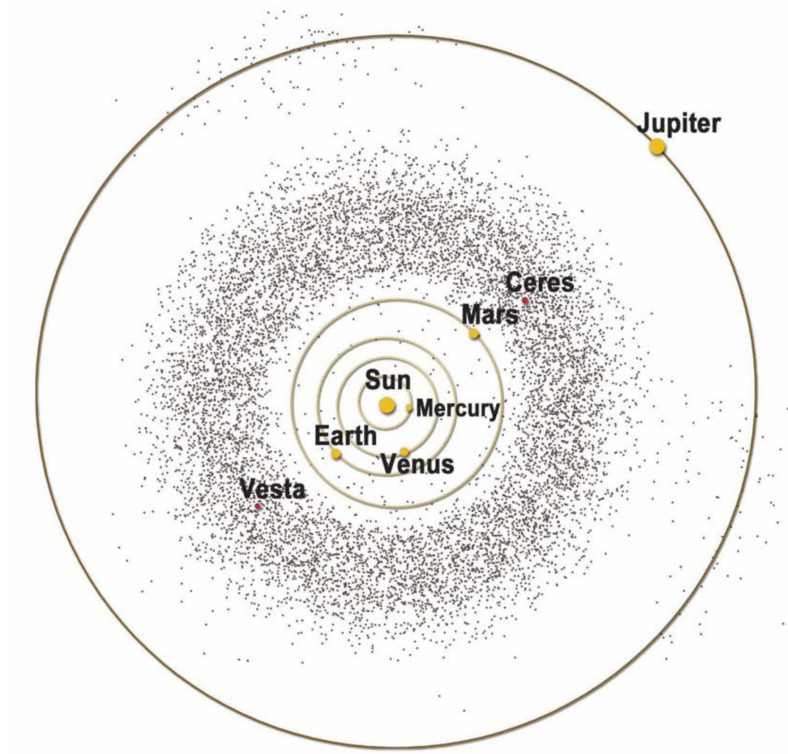

Figure 1: Schematic of the orbits of the five planets closest to our Sun and the locations of asteroids throughout the inner solar system. The main asteroid belt is located between the orbits of Mars and Jupiter and the Trojan asteroids are located along Jupiter's orbit. Notice that there are asteroids that cross the orbits of the Earth and other terrestrial planets. The protoplanets Vesta and Ceres, the targets of the Dawn mission, are indicated by red dots. (Credit: University of Maryland)

What is it like in the Main Belt?

This region is populated by small rocky bodies that range in size from small rocks to the largest body, 1 Ceres, that measures 959 km across (Millis et al., 1987). If Ceres were placed next to our Moon, it would only cover a third of the Moon's diameter (Bennett, Donahue, Schneider, & Voit, 2008).

Figure 2: Comparative sizes of the Earth, Moon, and Ceres (lower left). Though Ceres is the largest object in the asteroid belt, it is very small in comparison to our Earth and Moon. The diameter of the Moon is 3.7 times larger than the diameter of Ceres; you would need to line up 13 Ceres end to end to equal the diameter of the Earth. (Credit: NASA)

Ceres is actually massive enough that its gravity has pulled it into a sphere. It is therefore considered [and classified as] a dwarf planet, along with Pluto and some other large Kuiper Belt objects. For comparison, asteroid 4 Vesta is the third largest asteroid in the main belt, but at only 530 km across is not quite massive enough to be round (Thomas et al., 1997). There are currently over 440,000 known asteroids in the main belt, but there could be millions of bodies because many have not yet been discovered (JPL Small-Body Database). Even with this large number of asteroids, scientists conjecture that if you collected all of them together to form one body, it would only be 1,500 km across, slightly smaller than the Moon (http://astronomy.swin.edu.au/cms/astro/cosmos/A/Asteroid+Belt). This tells us that most asteroids are very small in comparison to Ceres, and that while the region is far more densely populated with asteroids than most parts our solar system, they are still far and few in between.

Why is the asteroid belt where it is?

A little background on how our solar system formed is needed to best describe just why the main asteroid belt is where it is. In the beginning of its formation, our solar system was a big cloud of gas and dust. Some event made it begin to spin, and it eventually spun down into a disk of matter swirling around our protosun (think of it as a baby Sun).

As material moved around the protosun, dust grains in the disk collided with each other and started sticking together to form larger rocks. These rocks in turn collided with other rocks and either gravity held them together or they broke into smaller pieces, depending on the nature of the collision and the relative gravity of the individual rocks. Over the next few million years, these rocks combined into larger and larger bodies and eventually, formed the planets and other large bodies we have today (Hillenbrand, 2008). Evidence of these collisions is seen on the surface of the planetary bodies, including asteroids, in the form of craters left by the impacts. Notice the impact cratered surface of asteroid 253 Mathilde in the image below.

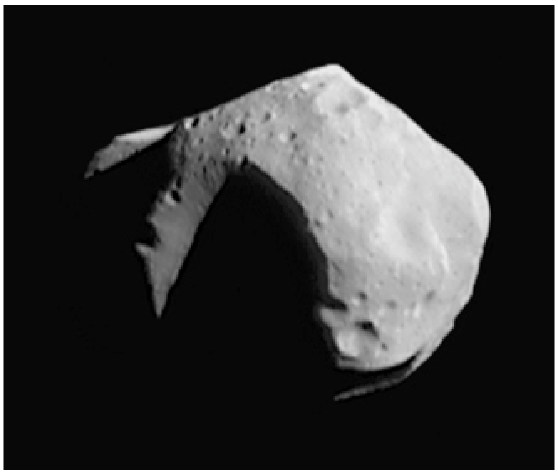

Figure 3: Asteroid 253 Mathilde taken by the NEAR spacecraft on June 27, 1997, from a distance of 1,500 miles. Mathilde has a radius of 52.8 km and orbits the Sun at a distance of 2.6 AU. (Credit: Near Earth Asteroid Rendezvous Mission [NEAR])

Collisions in the asteroid belt do not happen as frequently today as they did in the early years of our solar system, only about once every 100,000 years (Bennett et al., 2008). This explains why there are many small bodies in the asteroid belt, but it does not explain why one big planet like the Earth or Mars didn't form instead.

Why an asteroid belt and not a planet?

Recall that the asteroid belt lies between the orbits of Mars and Jupiter. Jupiter is the most massive body in our solar system after the Sun, and it therefore exerts a substantial amount of gravity on the objects around it. The competing gravitational influence of Jupiter and the Sun did not allow the bits and pieces of the asteroid belt to accrete into a larger planet. Further, scientists see asteroids orbiting within the belt in concentric clusters, a phenomenon that also can be explained by taking into account Jupiter's gravitational power.

Here's how: If an asteroid in the main belt is located such that it completes two whole orbits around the Sun in the same amount of time Jupiter completes one full orbit, it will reach its closest point to Jupiter once every other time it goes around the Sun. The asteroid will therefore feel a gravitational tug from Jupiter in the same place along its orbital. Think of this like pushing someone on a swing. To make them swing higher, you push them when they get closest to you. In the same way, the asteroid will feel a nudge from Jupiter when it gets to the spot in its orbit when it is closest to Jupiter. These nudges will eventually move the asteroid to a different orbit or throw it completely out of the main belt. An asteroid with this orbit has what is called a **resonant frequency** with Jupiter.

Resonances can occur at any whole-number combination of orbits. In the example above, the asteroid has a 2:1 resonance, meaning that it completes two orbits for every one Jupiter orbit. Other resonances are 3:1, 5:2, 7:3, etc. (http://astronomy.swin.edu.au/cosmos/K/Kirkwood+Gaps). These resonances also correspond to certain distances from the Sun because the amount of time it takes an object to orbit our Sun only depends on how far away from the Sun it orbits. If there is a collision in the main belt and an asteroid is bumped into a region that has a resonant frequency with Jupiter, it cannot stay there for long. It will either be thrown out or moved to a different orbit (http://astronomy.swin.edu.au/cosmos/K/Kirkwood+Gaps).

Over time, the regions of resonances have become depleted of asteroids and are called Kirkwood Gaps (after the scientist who first recognized them) illustrated in the graph below. The same gravitational force that created the Kirkwood Gaps has perturbed or disrupted the main belt region so much that a large planet could not form.

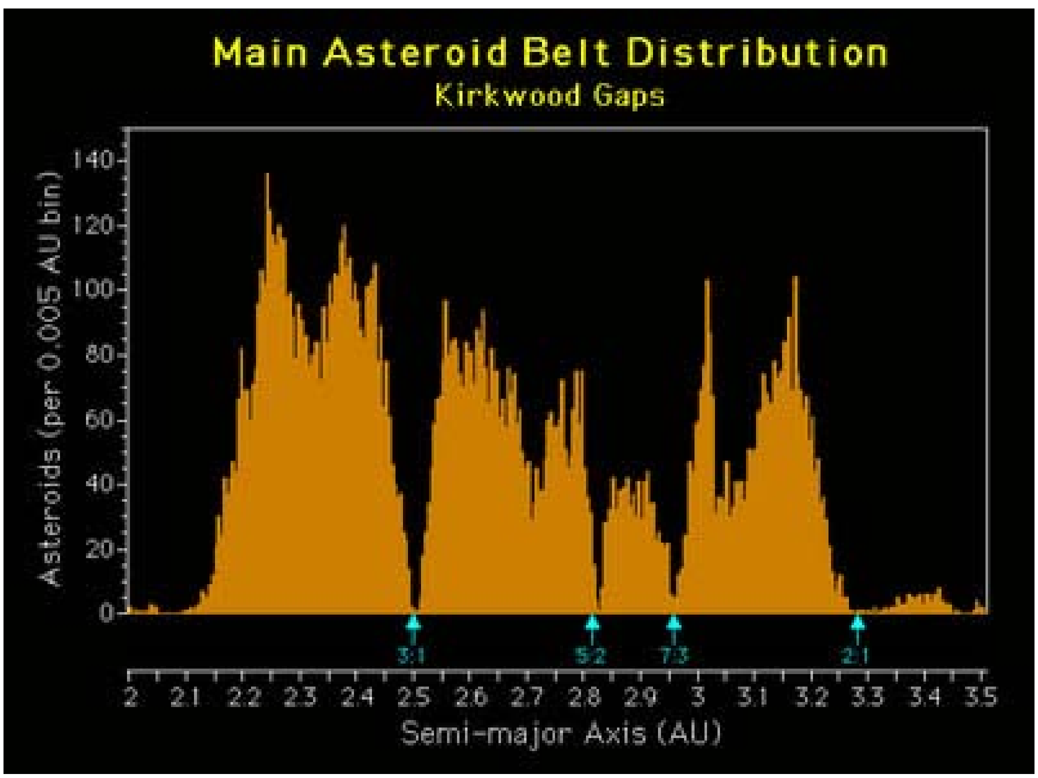

Figure 4: This histogram shows the distribution of asteroids in the Main Belt. Along the horizontal axis is the distance from the Sun, and along the vertical axis is the number of asteroids that orbit at this distance. The areas with low numbers of asteroids designated by the teal-colored arrows are regions of instability know as the Kirkwood Gaps. (Credit: Alan Chamberlain, NASA/JPL/Caltech)

What are asteroids like?

Some bodies in the asteroid belt, like Ceres, show evidence of ices and maybe water, but for the most part asteroids are rocky bodies. This is because they formed and still reside relatively close to the Sun. In our solar system, there is an invisible line around the Sun called the Frost Line. Outside of this line it is cold enough that materials with low boiling points like methane and oxygen, which are normally found as gases on Earth, can condense into solid material. These solid materials are called ices, much like when water freezes and forms water ice. If the ices were to be moved inside the Frost Line, the heat from the Sun would be too warm and they would sublimate, or turn from a solid into a vapor.

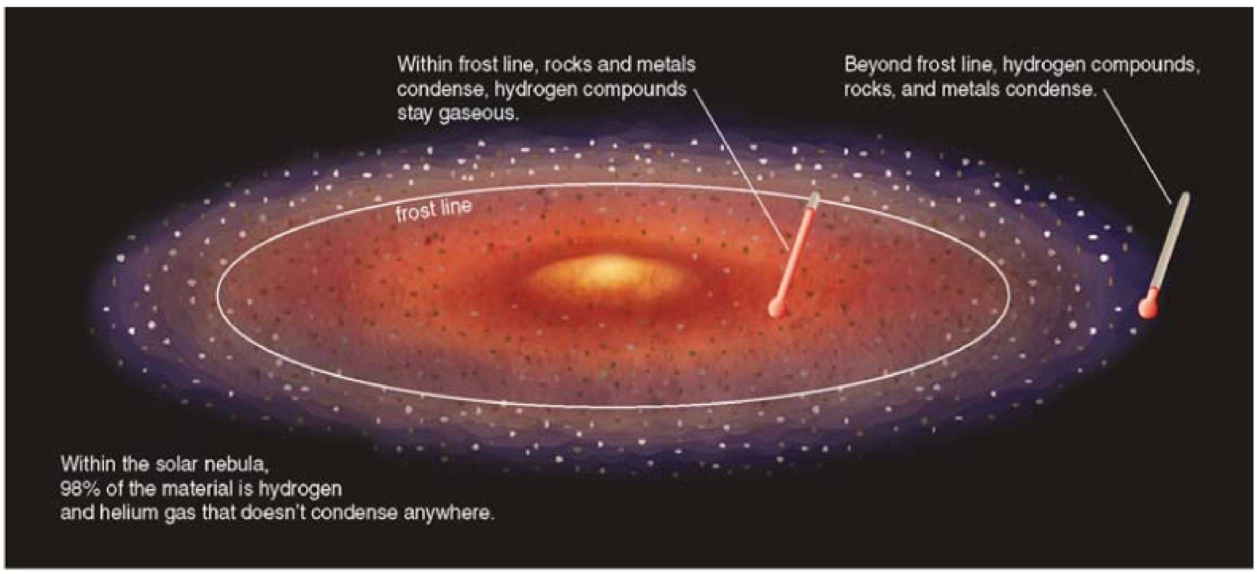

Figure 5: This diagram depicts the solar nebula from which our solar system formed. The white line designates the frost line inside which ices could not condense. Asteroids formed inside the frost line, so they are made only of rocks. Comets, on the other hand, form outside the frost line and are therefore made of both rocks and ices. (Credit: NASA/JPL)

This is the process that occurs when comets move close to the Sun in their orbit. Subliming ices vaporizing off the comet's nucleus scatter dust that reflect sunlight, forming the coma and tails that are visible when the comet comes close to Earth and the Sun. When the comet moves away from the Sun and beyond the Frost Line, its ices stop sublimating, the coma and tail no longer form, and the comet becomes an inactive, icy, rocky body.

Therefore, the Frost Line defines the region beyond which what are considered volatile gasses here on Earth form ices. Unlike ices, materials with higher boiling points, like rocks and metals, can condense at the much higher temperatures closer to the Sun. As a result, metals and rocks can exist both inside and outside of the Frost Line and are found throughout the solar system.

The Frost Line lies in the neighborhood of 3.5 AU (there is not an exact location), which is just beyond the region where the majority of asteroids orbit (http://astronomy.swin.edu.au/cms/astro/cosmos/A/Asteroid+Belt).

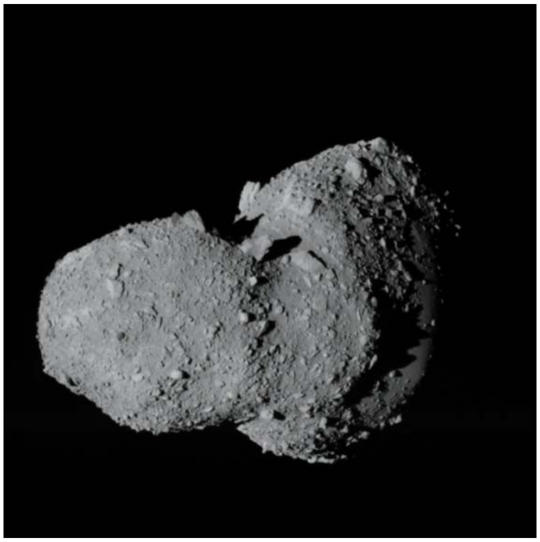

Figure 6: Up-close view of asteroid 25143 Itokawa imaged by the Japanese spacecraft Hayabusa. Notice the individual rocks visible on the surface. Itokawa is 0.33 km in diameter and orbits the Sun at 1.3 AU. (Credit: ISAS/JAXA)

Ices therefore cannot form in most of the main asteroid belt because it is too close to the Sun. As a result, a majority of asteroids are rocky bodies as opposed to comets, which are rocky and icy bodies that originated further out in our Solar System.

Are all asteroids the same?

All asteroids were formed in the same region of the solar system, but they are not all made out of the same materials. The reason for the variation in the composition of asteroids throughout the main belt is not well known. They are classified according to their color and reflectance spectra, which are associated with their composition

Asteroids are also classified into groups called families that share similar orbital characteristics like eccentricity (shape of orbit) or inclination (tilt of orbit). Families are formed when a collision in the main belt breaks up a large asteroid into many smaller pieces. The small pieces become members of a family and are all the same spectral type because they originated from the same parent asteroid (Michel, Tanga, Benz, & Richardson, 2002).

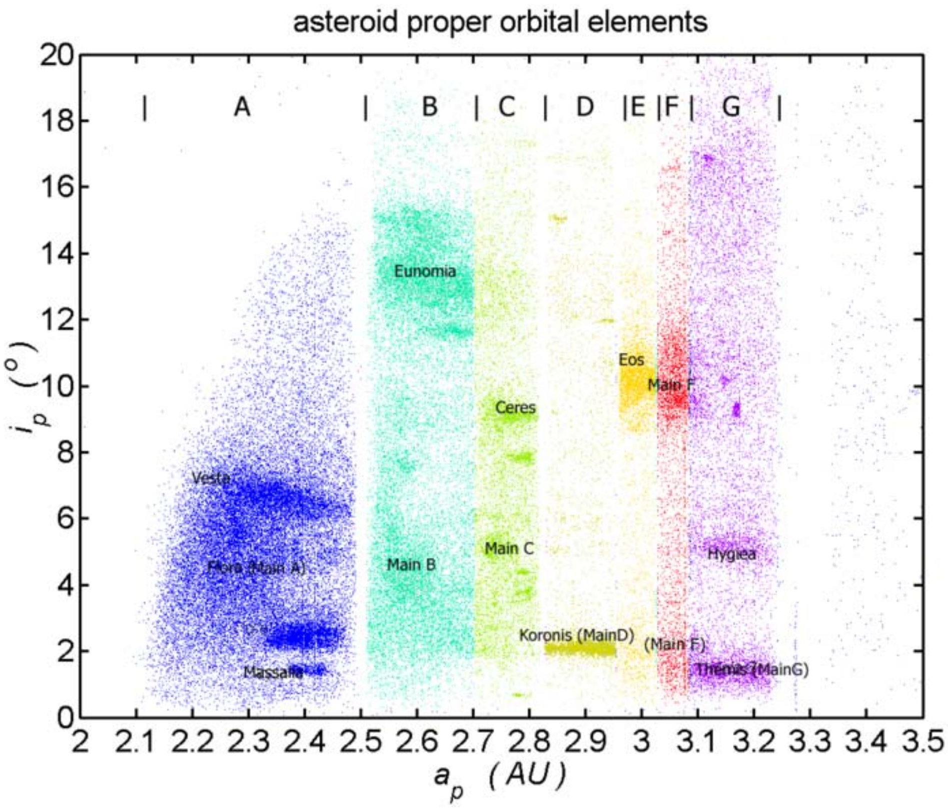

Figure 7: This plot highlights some of the major families or groups in the asteroid belt. Vesta (group A) and Ceres (group C) are labeled on the plot. Asteroid proper orbital elements (n.d.). Source: http://en.wikipedia.org/wiki/File:AsteroidIncAu.png (made available under a Creative Commons License).

Vesta and Ceres are a special class of asteroids called protoplanets. Recall the current theory of planet formation says that planets formed by accretion, in which pieces of rock and gas stick together through impacts to form larger and larger bodies. Thought to be small planets, or an intermediate phase in planet formation, protoplanets are bodies that did not accrete enough mass and grow large enough to become a planet. The Dawn mission is designed to gain more insight into planet forming processes from studying Vesta and Ceres (McCord, McFadden, Russell, Sotin, & Thomas, 2006).

How do we know what asteroids are made of?

One way astronomers have learned about asteroid composition is through studying meteorites. When asteroids collide in the main belt, some of the fragments break off as meteoroids, the name given to the fragments while they are in space. If these meteoroids are deflected into an unstable orbit, like a 3:1 resonance with Jupiter, they can make their way to Earth. When they hit the Earth's atmosphere, meteoroids start to burn up and we see them as meteors or shooting stars in the sky. If the fragments make it through the atmosphere to the ground, then they are considered meteorites. Thus scientists can study pieces of the main asteroid belt right in their labs.

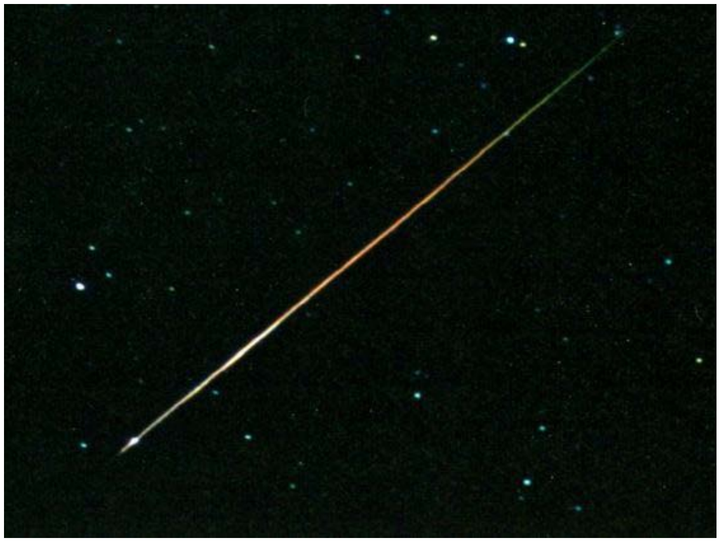

Figure 8: This image is of a meteor during the Perseid meteor shower on August 13 in Sedona, Arizona, USA. The Perseid meteor shower happens twice a year when the Earth passes through the trail of comet Swift-Tuttle. (Credit: Dirk Obudzinski. Courtesy NASA)

How do we know we have pieces of the asteroid belt here on Earth? Scientists can perform a procedure called spectral analysis with space and ground-based telescopes on asteroids in their orbits as well as on the samples found on Earth. To do this, a device called a spectrometer is used to read light signatures reflected by materials. Each mineral on an asteroid's surface reflects light in a distinct pattern, and the unique combination of patterns is the asteroid's spectral signature, similar to an individual's fingerprint.

Scientists can determine which asteroid or family of asteroids a meteorite came from by matching their spectral fingerprints. A certain set of meteorites, called HED meteorites, are thought to come from Vesta and its family of asteroids. Scientists speculate that the collision that caused the huge crater on Vesta may be the source of the HED meteorites. Thus, scientists can learn about the asteroid by examining the composition of the meteorite with the same spectral fingerprint. Meteorites are invaluable in our study of asteroids.

Are asteroids only located in the main belt?

Asteroids are found in other parts of the solar system. Figure 1 shows the positions of all the asteroids in the inner solar system. There are asteroids that cross the orbit of Earth, and these are called Near Earth Objects. Astronomers are constantly searching for and monitoring these asteroids to assess the probability of a collision with Earth. As of 19 June 2009, there were 6210 known NEOs and none that looked threatening (http://neo.jpl.nasa.gov/stats/). Using meteorites to determine the composition of asteroids is very important because this knowledge will influence how we would deter a hazardous asteroid on a collision course with Earth.

There are also asteroids that lie along Jupiter's orbit called the Trojan asteroids. These asteroids either follow behind or lead in front of the planet. They will never collide with Jupiter because they are locked into their orbits by the planet's strong gravitational field.

As of 9 June 2009, there were 1811 know asteroids leading and 1370 trailing Jupiter (http://www.cfa.harvard.edu/iau/lists/JupiterTrojans.html).

Conclusion?

With this foundation on what and how we study the main asteroid belt, readers are primed to delve deeper into the Dawn mission's primary goal:

> . . . To characterize the conditions and processes of the solar system's earliest epoch by investigating in detail two of the largest protoplanets remaining intact since their formations. Ceres and Vesta reside in the extensive zone between Mars and Jupiter together with many other smaller bodies, called the asteroid belt. Each has followed a very different evolutionary path constrained by the diversity of processes that operated during the first few million years of solar system evolution (http://dawn.jpl.nasa.gov/mission/index.asp).

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